Higgs Properties and Fourth Generation Leptons

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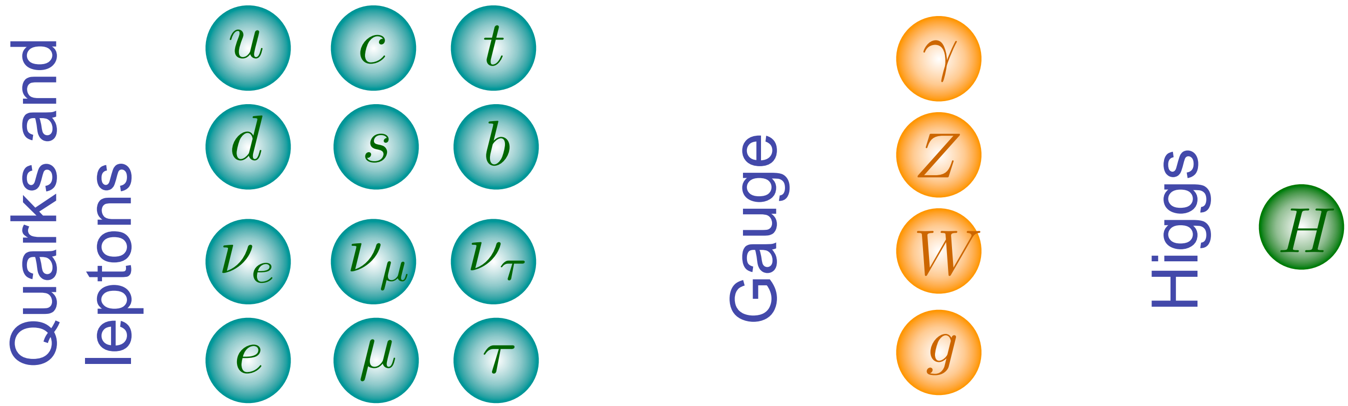
Based on arXiv:1107.1490

1. Introduction
2. The model
3. Higgs production and decay
4. Higgs mass bounds
5. Conclusion

SUSY2011, August 30, 2011

1. Introduction

Standard model (SM) is a nice model framework which well explains phenomena in particle physics so far



Quarks and leptons have a structure called generation

In SM, the number of generation is three; however, there is no guiding principle to predict it

Fourth generation is a possible extension; it is phenomenologically acceptable

- It is not excluded by electroweak precision measurement [Kribs,Plehn,Spannowsky,Tait '07]
- Direct search gives mass bounds for fourth generations:

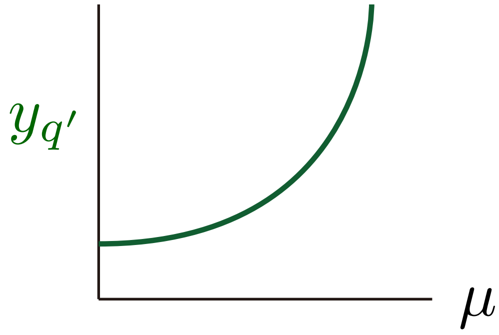
Quark	Lepton
$m_{u',d'} \gtrsim 330$ GeV	$m_{e'} \gtrsim 100$ GeV
	$m_{\nu'} \gtrsim 45(90)$ GeV

[CDF '09, PDG]

(for stable (unstable) case)

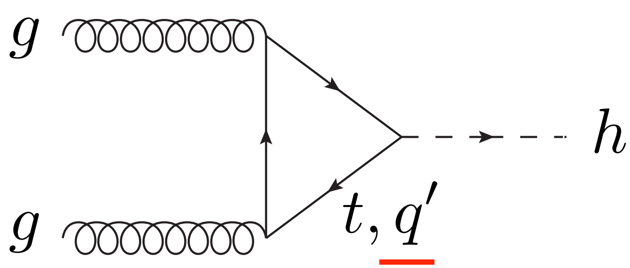
Due to those mass bound, 4th generation should be heavy; so their Yukawa couplings are larger than $O(1)$ when we consider chiral 4th generation

- Such large Yukawa couplings, especially for quarks, have Landau poles



μ : renormalization scale

- In phenomenology, Higgs production rate is significantly enhanced by 4th generation loop, compared to its SM-value



However, the situation changes when one considers *vector*-like 4th generation (chiral 4th generation plus its “mirror”)

[Perez,Wise ’11]

$$Q'_L = \begin{pmatrix} u'_L \\ d'_L \end{pmatrix} \quad u'_R \quad d'_R \qquad\qquad Q''_R = \begin{pmatrix} u''_R \\ d''_R \end{pmatrix} \quad u''_L \quad d''_L$$

$$L'_L = \begin{pmatrix} \nu'_L \\ e'_L \end{pmatrix} \quad \nu'_R \quad e'_R \qquad\qquad L''_R = \begin{pmatrix} \nu''_R \\ e''_R \end{pmatrix} \quad \nu''_L \quad e''_L$$

Chiral 4th generation

Mirror generation

In such a model, there exist bare mass terms for the 4th generations,

$$\Delta\mathcal{L}_q = -M_Q \bar{Q}'_L Q''_R - M_U \bar{u}'_R u''_L - M_D \bar{d}'_R d''_L + \cdots$$

Then, 4th generation quark masses can be large without considering large Yukawa

- 4th generation quark Yukawa couplings don't have Landau poles
- They are expected to have little effect on Higgs production rate

For lepton sector, if we assume a $U(1)$ symmetry, bare mass terms for 4th generation leptons are forbidden, e.g., $U(1)_L$ (see later)

[Perez,Wise '10; Dulaney,Perez,Wise '10]

$$\Delta\mathcal{L}_l = -h'_E \bar{L}'_L H e'_R - h''_E \bar{L}''_R H e''_L + \cdots$$

H : Higgs doublet

We consider vector-like 4^{th} generation scenario where

- 4^{th} generation quarks have bare masses
- 4^{th} generation leptons get their masses from weak symmetry breaking

In the framework, we study

- Higgs properties, especially focusing on its production and decay rates at the LHC
- Impact of 4^{th} generation on Higgs potential

Outline

1. Introduction
2. The model
3. Higgs production and decay
4. Higgs mass bounds
5. Conclusion

2. The model

We consider a model with a 4th generation fermion ("primed") and its mirror ("double primed") in addition to SM particles

	Chiral 4th generation		Mirror generation	
	$Q'_L = \begin{pmatrix} u'_L \\ d'_L \end{pmatrix}$	$u'_R \quad d'_R$	$Q''_R = \begin{pmatrix} u''_R \\ d''_R \end{pmatrix}$	$u''_L \quad d''_L$
	$L'_L = \begin{pmatrix} \nu'_L \\ e'_L \end{pmatrix}$	$\nu'_R \quad e'_R$	$L''_R = \begin{pmatrix} \nu''_R \\ e''_R \end{pmatrix}$	$\nu''_L \quad e''_L$
$SU(2)$	doublet	singlet	doublet	singlet
$U(1)_Y$	Same as the existing generations in SM			

Then, new gauge invariant terms are introduced in Lagrangian;

$$\begin{aligned}\Delta\mathcal{L}_q = &- M_Q \bar{Q}'_L Q''_R - M_U \bar{u}'_R u''_L - M_D \bar{d}'_R d''_L \\ &- h'_U \bar{Q}'_L \epsilon H^* u'_R - h''_U \bar{Q}''_R \epsilon H^* u''_L \\ &- h'_D \bar{Q}'_L H d'_R - h''_D \bar{Q}''_R H d''_L + \mathrm{h.c.}\end{aligned}$$

bare mass

Yukawa

$$\begin{aligned}\Delta\mathcal{L}_l = &- h'_E \bar{L}'_L H e'_R - h''_E \bar{L}''_R H e''_L \\ &- h_N \bar{L}'_L \epsilon H^* \nu'_R - h''_N \bar{L}''_R \epsilon H^* \nu''_L + \mathrm{h.c.}\end{aligned}$$

Yukawa

Here we assume a $U(1)$ symmetry in lepton sector to forbid bare mass terms

One of the examples is gauged baryon&lepton number

In SM, baryon&lepton number are conserved; so one can consider SM as effective theory of a model where baryon&lepton number are gauged and spontaneously break at very high energy [Foot,Joshi,Lew ’89]

Here in such a framework, we consider seesaw scenario for ordinary generation neutrinos in lepton sector

For seesaw scenario, we consider a scalar with lepton number 2, which breaks $U(1)_L$

- We can introduce the terms to create heavy Majorana neutrino masses for ordinary generations
- The terms which create bare mass terms for 4th generation leptons are forbidden

[Perez,Wise '10]

$$\underbrace{a_\nu S_L^*}_{L=-2} N_R N_R + \mathrm{h.c} \xrightarrow[\langle S_L \rangle \neq 0]{\cancel{U(1)_L}} M_\nu N_R N_R + \mathrm{h.c}$$

$S_L \bar{e}''_R e'_L + \mathrm{h.c.}$ (forbidden)

S_L : scalar, which breaks $U(1)_L$

So the additional Lagrangian we consider is (again),

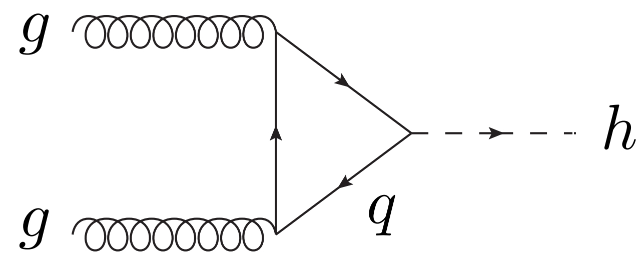
$$
\begin{aligned}
\Delta\mathcal{L}_q = &- M_Q \bar{Q}'_L Q''_R - M_U \bar{u}'_R u''_L - M_D \bar{d}'_R d''_L \\
&- h'_U \bar{Q}'_L \epsilon H^* u'_R - h''_U \bar{Q}''_R \epsilon H^* u''_L \\
&- h'_D \bar{Q}'_L H d'_R - h''_D \bar{Q}''_R H d''_L + \text{h.c.}
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_l = &- h'_E \bar{L}'_L H e'_R - h''_E \bar{L}''_R H e''_L \\
&- h_N \bar{L}'_L \epsilon H^* \nu'_R - h''_N \bar{L}''_R \epsilon H^* \nu''_L + \text{h.c.}
\end{aligned}
$$

3. Higgs production and decay

Higgs production

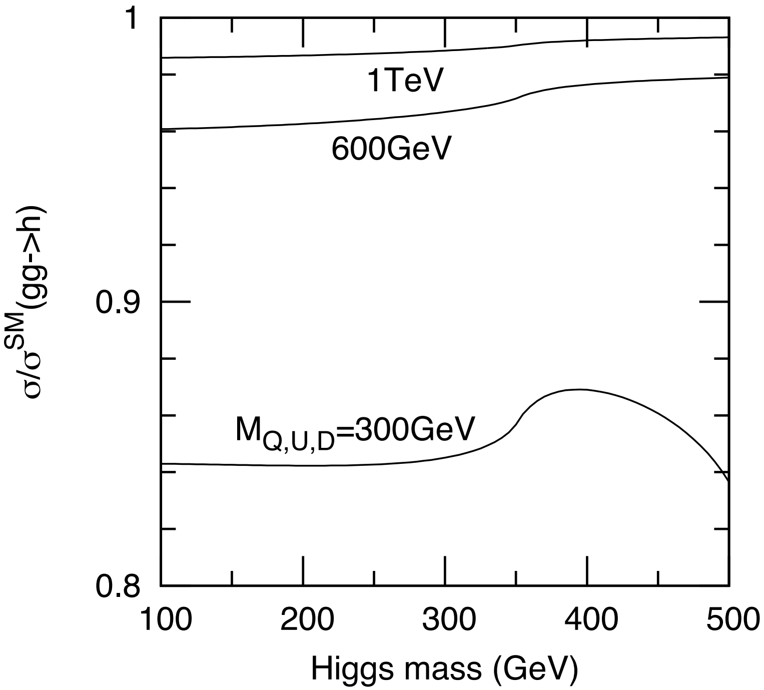
Higgs production rate is dominated by gluon fusion process at the LHC



In our model, 4^{th} generation quarks give new contributions in addition to top

As I mentioned in the Introduction, 4^{th} generation quarks have bare masses in our model so they decouple in low energy effective theory when their masses are large

Numerical results



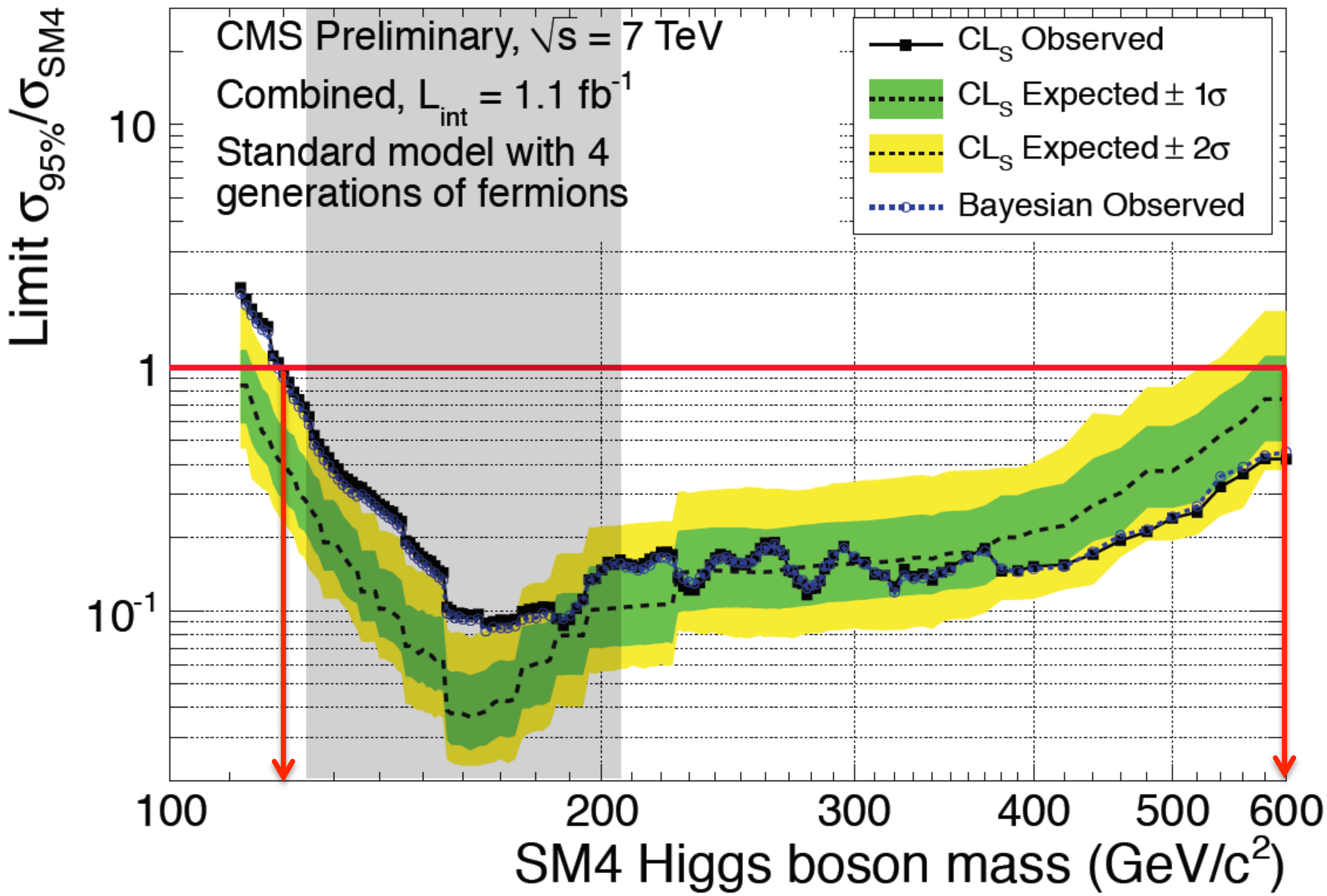
$M_{Q,U,D}$: Bare mass parameters

$$\frac{h'_{U,D}v}{\sqrt{2}} = \frac{2h''_{U,D}v}{\sqrt{2}} = 60 \text{ GeV}$$

Higgs production rate quickly approaches its SM-value

cf. in chiral 4th generation scenario, the ratio is ~ 9

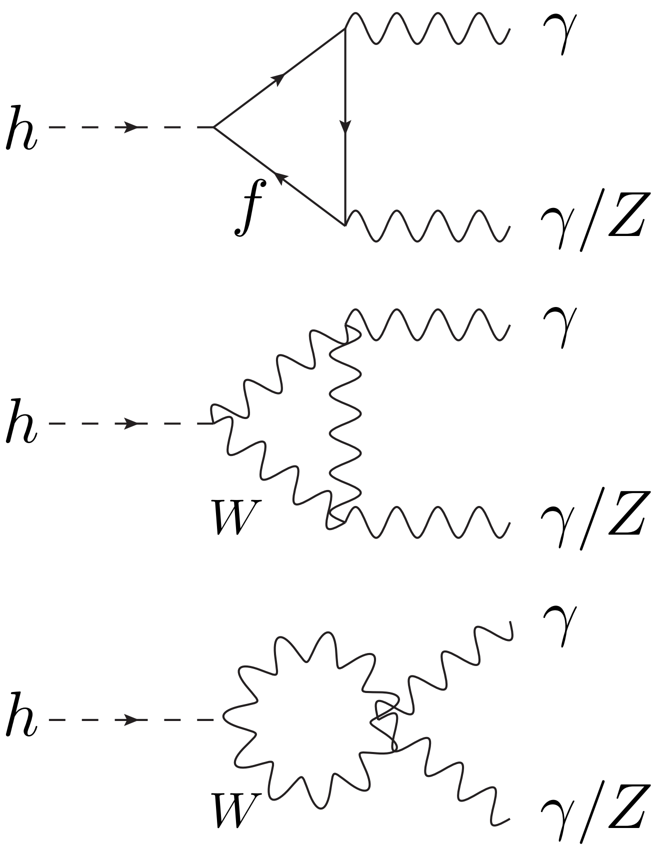
In chiral 4th generation scenario, $120\ \mathrm{GeV} \leq m_h \leq 600\ \mathrm{GeV}$ is excluded by LHC due to the enhancement of the Higgs production rate; this exclusion is invalid in our case

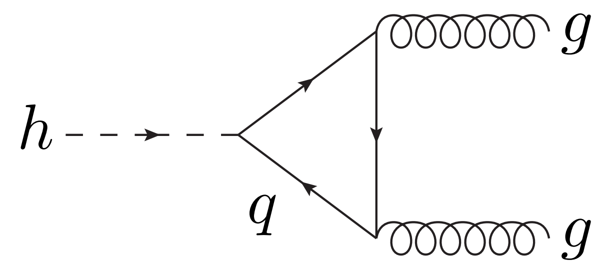


[Talk given by CMS collaboration at EPS '11]

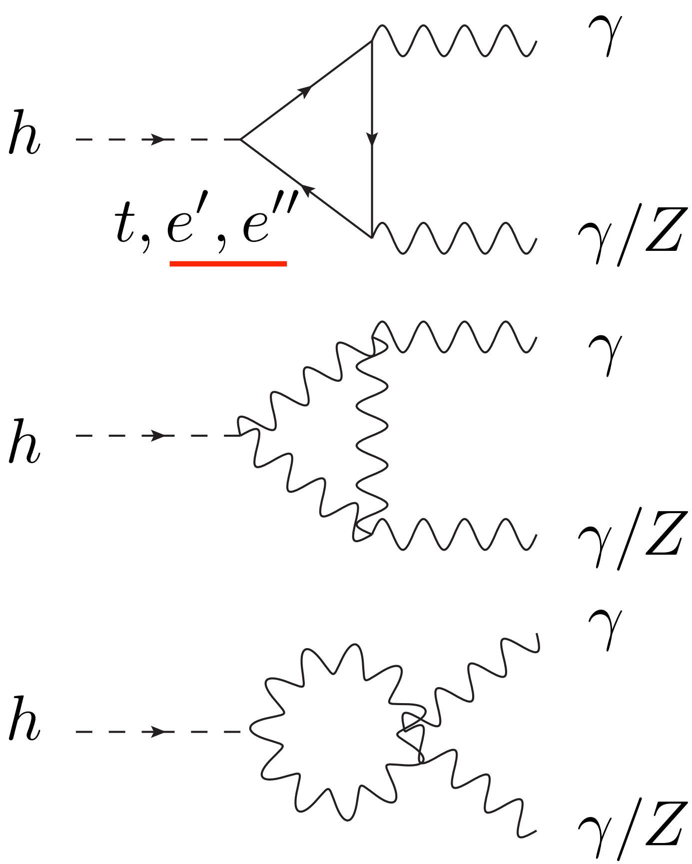
Higgs decay

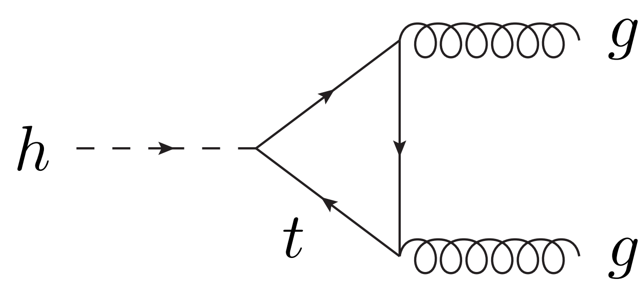
The extra generation makes changes in the following three decay processes in Higgs decay; $h \to \gamma\gamma,\ \gamma Z$ and gg





Here, we already know that 4th generation quarks decouple rapidly; so we neglect the effect of 4th generation quarks for simplicity in the following calculation

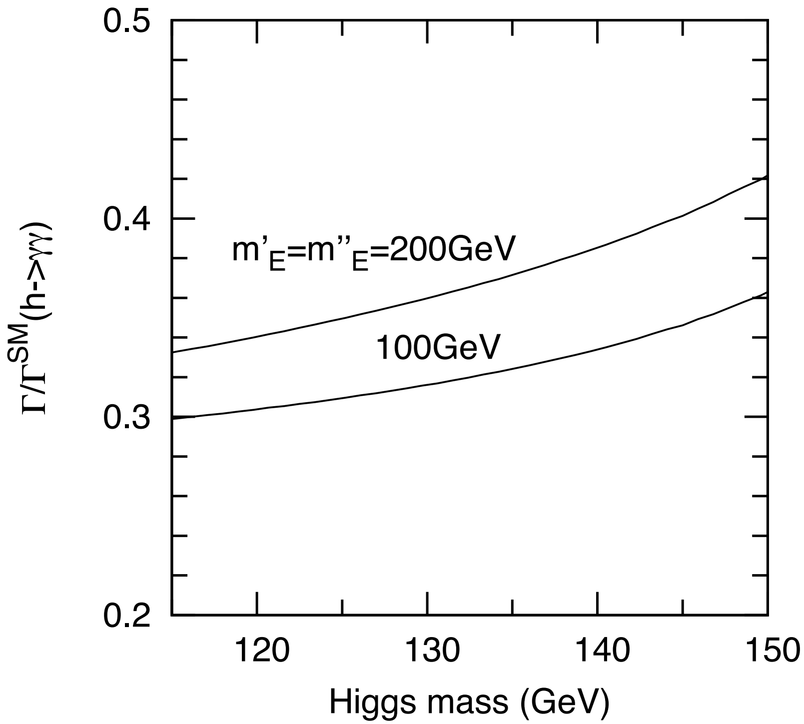




Numerical results

(i) $h \to \gamma\gamma$

- The decay rate turns out to be $30\text{-}40\%$ of its SM value
- The dependence of the new charged lepton masses on this result is weak



$m'_E(m''_E)$: Chiral (mirror) 4th generation charged lepton mass

c.f., The decay rate :

$$\Gamma_{h\to\gamma\gamma} \propto \left|\frac{4}{3}I(r_t) + \underline{I(r_{E'}) + I(r_{E''})} + K(r_W)\right|^2$$

$r_X = m_h^2/4m_X^2$ for particle X

$I(x), K(x)$: Analytic function

Fermion loops and W boson loop interfere destructively

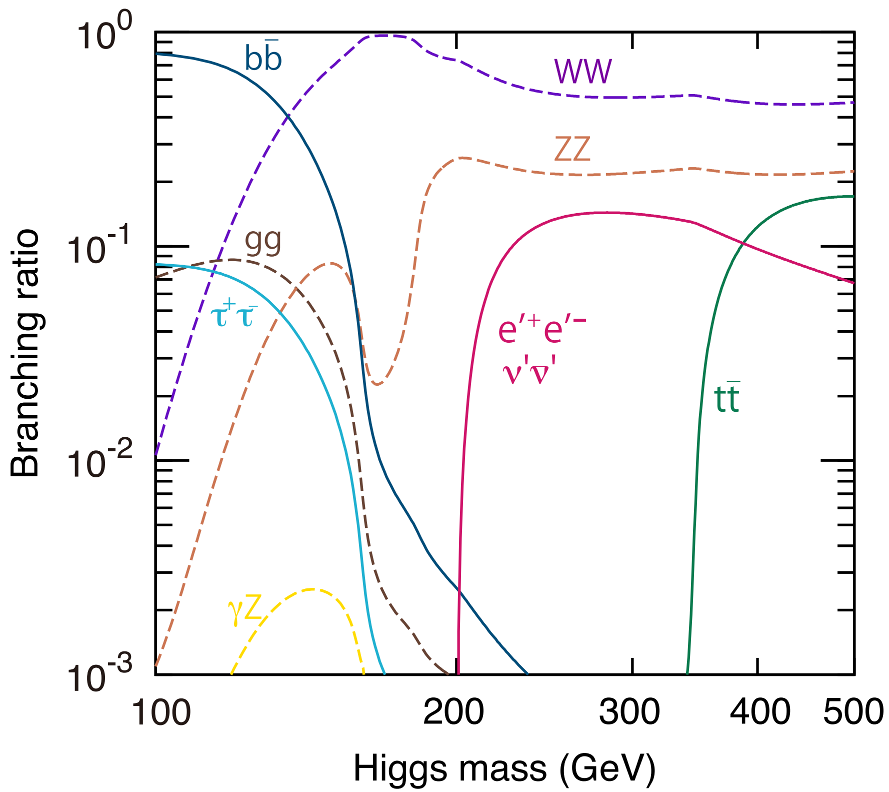
(ii) $h \rightarrow \gamma Z$

The decay rate is almost same as its SM-value

(iii) $h \rightarrow gg$

The decay rate is unchanged since 4^{th} generation quarks decouple

Branching ratios

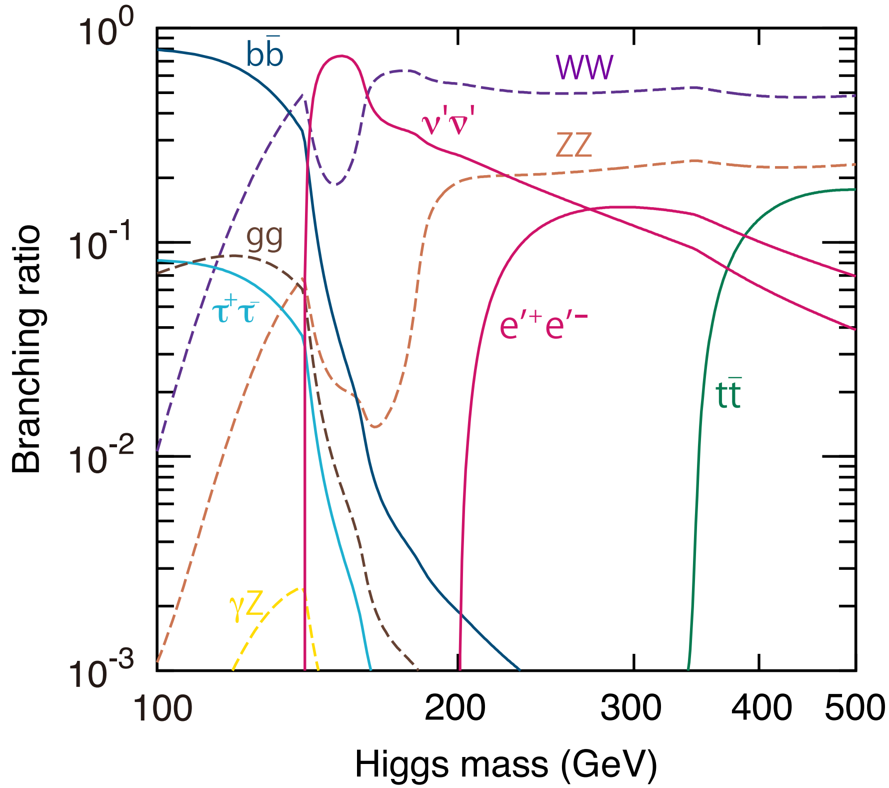


$m'_E = m''_E = 100 \text{ GeV}$

$m'_N = m''_N = 100 \text{ GeV}$

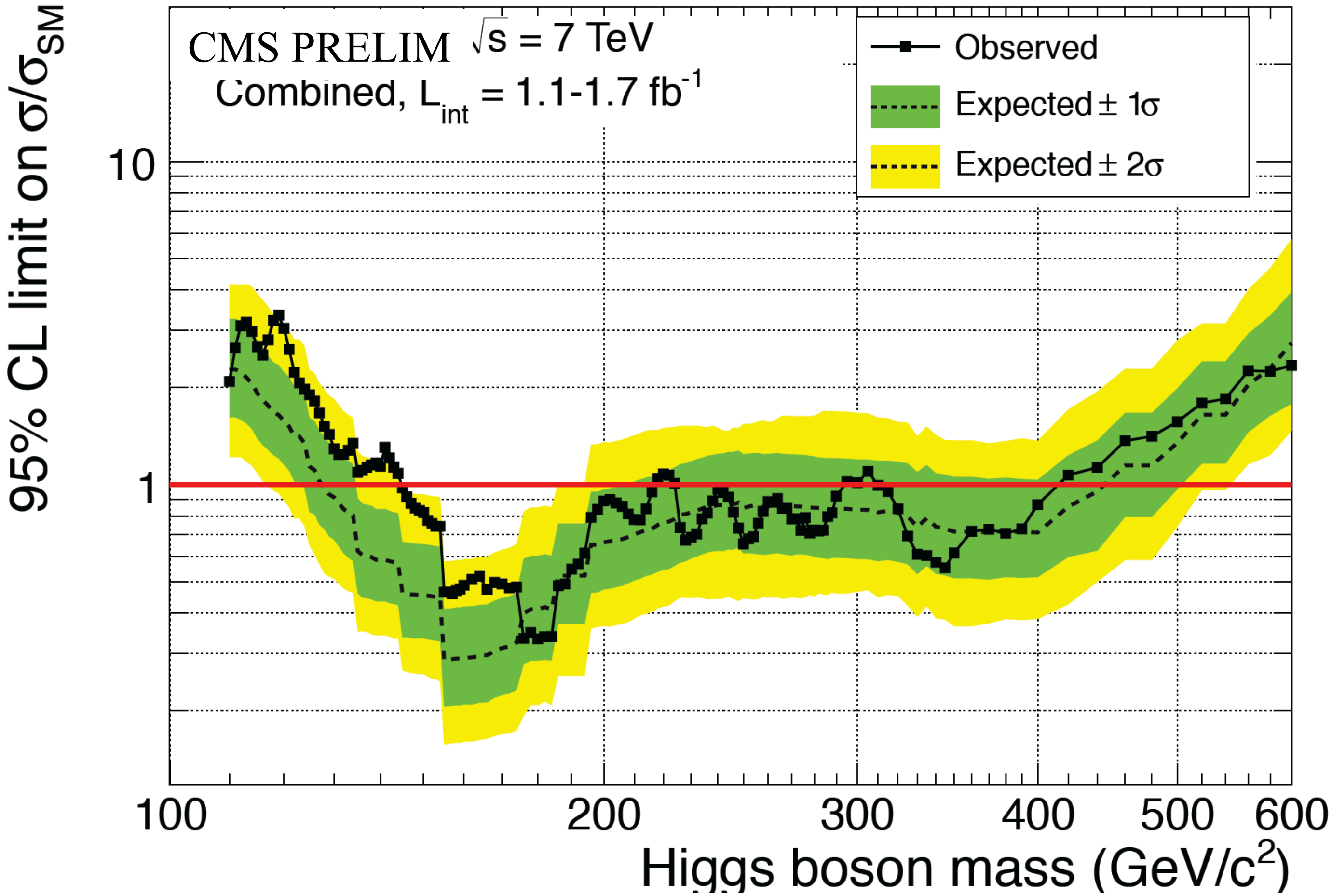
using HDECAY package [Djouadi,Malinowski, Spira'98]

- $m_h < 200$ GeV : Branching ratios are very similar to those in SM except for $h \to \gamma\gamma$
- $m_h > 200$ GeV : Branching ratios for $h \to WW, ZZ$ are reduced to ~70% of its SM-value due to the appearance of new decay modes, $h \to e'^+e'^-$, etc.



$$m'_E = m''_E = 100\ \text{GeV}$$
$$m'_N = m''_N = 70\ \text{GeV}$$

When the neutral 4th generation leptons are lighter than gauge bosons, the reduction of branching ratios for $h \to WW, ZZ$ are much drastic; the branching ratios turn out to be ~30% of its SM-value around $m_h = 150\ \text{GeV}$



[Talk given by CMS collaboration at LP ’11]

- Higgs mass of $200\text{-}400\ \mathrm{GeV}$ exclusion is partially invalid because WW, ZZ modes are reduced to ~70% of its SM-values
- $145\text{-}200\ \mathrm{GeV}$ exclusion may also be invalid when new neutral lepton are lighter than gauge bosons

4. Higgs mass bounds

As mentioned in Introduction, 4^{th} generation *quarks* don't have any Landau poles; however, 4^{th} generation *leptons* may have

So 4^{th} generation lepton Yukawa couplings may affect Higgs potential,

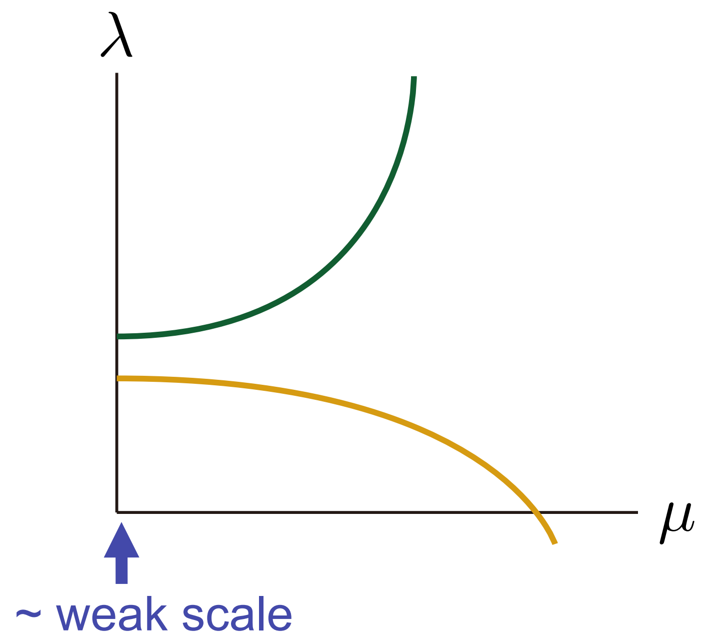
$$V^H = -\mu_H^2 |H|^2 + \lambda |H|^4$$

In SM, Higgs quartic coupling could be divergent or get negative at a certain scale (which is interpreted as a cutoff of theory) depending on its value at weak scale

[Cabbie,Maiani,Parisi,Petronzi ’79;Beg,Panagiotakopoulos,Sirloin ’84;Lindner ’86;Altarelli,Isidori ’94;Casas,Espinosa,Quiros 94’;Hambye,Riesselmann ’96]

This fact is seen in the renormalization group equation (RGR) for λ ,

$$16\pi^2\mu\frac{\partial\lambda}{\partial\mu} = \underline{24\lambda^2} + 12\lambda y_t^2 \underline{- 6y_t^4}$$



→ The upper and lower bound for Higgs mass are obtained for a fixed cutoff

We have performed the same analysis in our model to get Higgs mass bounds

First we solve RGEs for Yukawas,

$$16\pi^2\mu\frac{\partial h_E}{\partial\mu} =\frac{7}{2}h_E^3 + h_E\left(3y_t^2+\frac{1}{2}h_N^2\right) - h_E\left(\frac{9}{4}g_2^2+\frac{15}{4}g_1^2\right),$$

$$16\pi^2\mu\frac{\partial h_N}{\partial\mu} =\frac{7}{2}h_N^3 + h_N\left(3y_t^2+\frac{1}{2}h_E^2\right) - h_N\left(\frac{9}{4}g_2^2+\frac{3}{4}g_1^2\right),$$

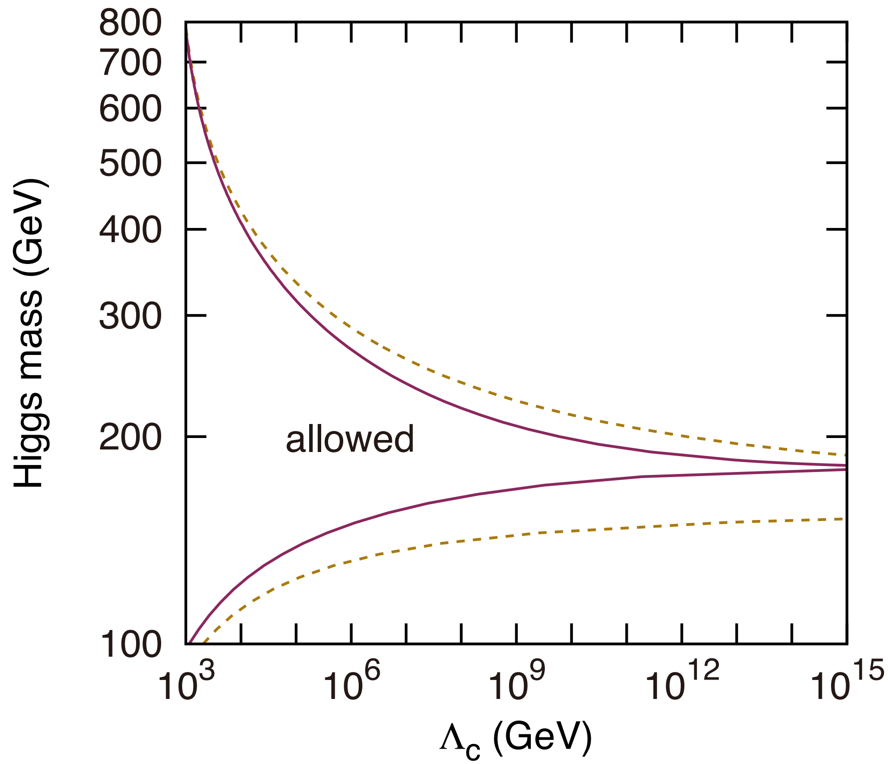
$$16\pi^2\mu\frac{\partial y_t}{\partial\mu} =\frac{9}{2}y_t^3 + y_t\left(2h_E^2+2h_N^2\right) - y_t\left(8g_3^2+\frac{9}{4}g_2^2+\frac{17}{12}g_1^2\right)$$

Here we have assumed $h'_E = h''_E \equiv h_E, h'_N = h''_N \equiv h_N$ for simplicity

After solving those Eqs, we solve the RGE for λ:

$$16\pi^2\mu\frac{\partial\lambda}{\partial\mu} =24\lambda^2 + 4\lambda\left[3y_t^2 + \underline{2(h_E^2+h_N^2)}\right] - 2\left[3y_t^4 + \underline{2(h_E^4+h_N^4)}\right]$$
$$- 3\lambda(3g_2^2+g_1^2) + \frac{3}{8}\left[2g_2^4+(g_2^2+g_1^2)^2\right]$$

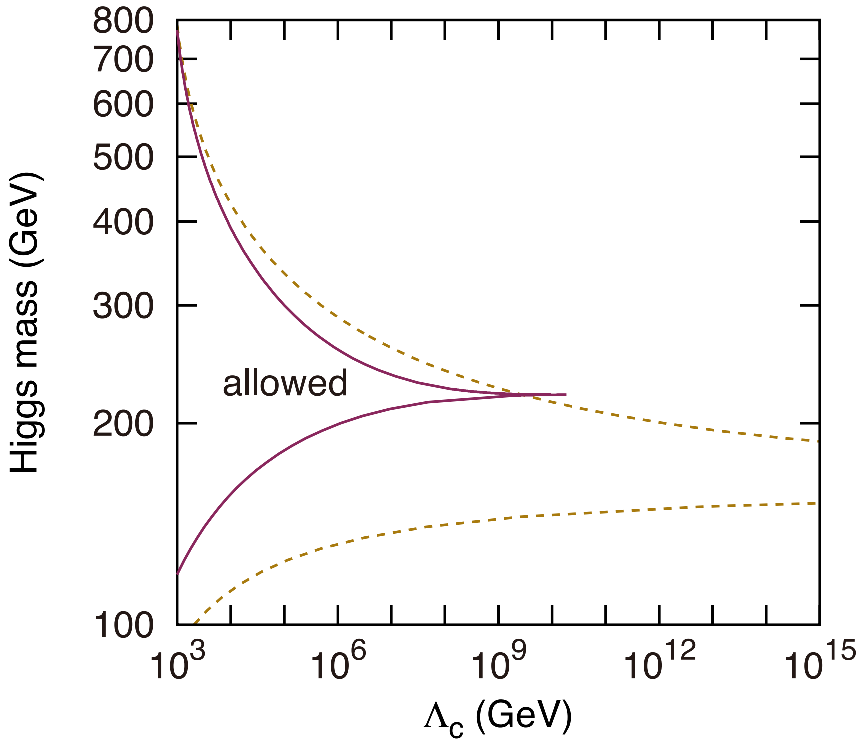
Numerical results



$m'_E = m''_E = 100$ GeV
$m'_N = m''_N = 100$ GeV
(solid purple)

SM result (dotted)

- No Landau pole for 4th generation Yukawa and top Yukawa couplings up to Planck scale
- Higgs mass bounds get more strict



$$m'_E = m''_E = 150 \text{ GeV}$$
$$m'_N = m''_N = 150 \text{ GeV}$$

When the masses of 4th generation leptons are larger, their Yukawa couplings have Landau poles

As a consequence, constraint for Higgs mass becomes more stringent

5. Conclusion

We have considered vector-like 4^{th} generation where new leptons get their mass by weak symmetry breaking but new quarks do not

In the framework, we have studied their impact on Higgs properties and found that

- Higgs decay rate for $h \to \gamma\gamma$ is reduced to 30-40% of its SM-value, while Higgs production rate is the same as in SM
- Higgs mass bounds turn out to be more stringent

Backups

Higgs-quark interaction

$$\mathcal{L}^{q}_{\mathrm{Higgs}} = -\frac{\mu_{U_1}}{v} h\bar{U}_1 U_1 - \frac{\mu_{U_2}}{v} h\bar{U}_2 U_2 - \frac{\mu_{D_1}}{v} h\bar{D}_1 D_1 - \frac{\mu_{D_2}}{v} h\bar{D}_2 D_2 - \frac{m_t}{v} h\bar{t}t$$

U_i, D_i : mass eigenstate

Then, cross section for gluon fusion is given by

$$\frac{\sigma_{gg\to h}}{\sigma^{\mathrm{SM}}_{gg\to h}} = \left| 1 + \sum_{i=1,2} \left[\frac{\mu_{U_i}}{M_{U_i}} I\left(r_{U_i}\right) + \frac{\mu_{D_i}}{M_{D_i}} I\left(r_{D_i}\right) \right] / I(r_t) \right|^2$$

$r_t = m_h^2 / 4m_t^2$

$r_{U_i,D_i} = m_h^2 / 4M^2_{U_i,D_i}$

$I(x)$: an analytic function

Higgs-lepton interaction

$$\mathcal{L}^{l}_{\rm Higgs} = -\frac{m'_E}{v} h\bar{e}' e' - \frac{m''_E}{v} h\bar{e}'' e'' - \frac{m'_N}{v} h\bar{\nu}' \nu' - \frac{m''_N}{v} h\bar{\nu}'' \nu''$$

e', e'', ν', ν'' : Dirac particles

$m'_E = h'_E v/\sqrt{2}, m''_E = h''_E v/\sqrt{2},$ etc.

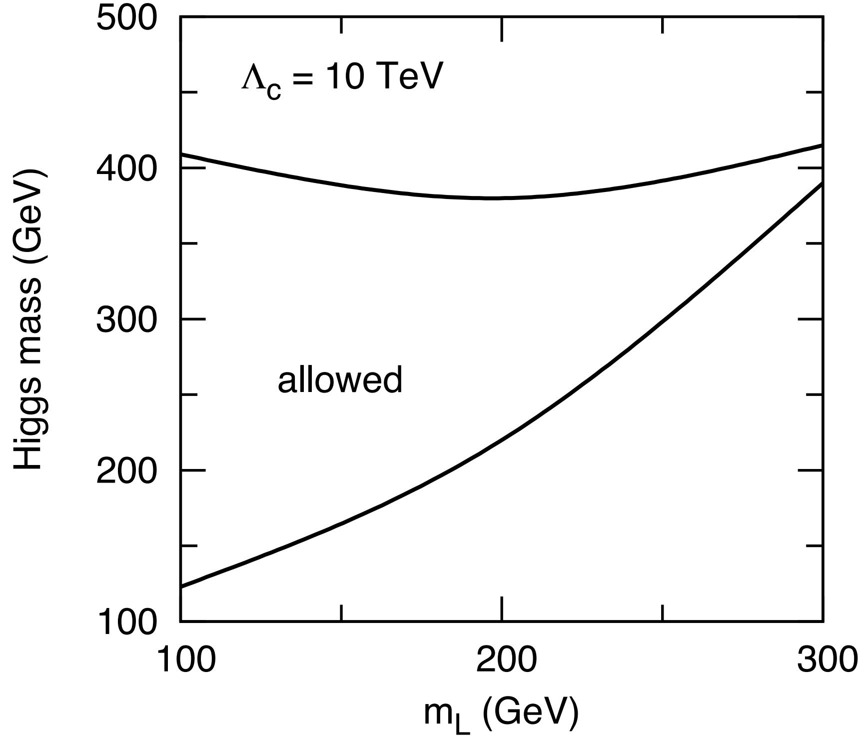
Higgs decay rate

m_h (GeV)	$\mathrm{Br}/\mathrm{Br}^{\mathrm{SM}}(WW)$	$\mathrm{Br}/\mathrm{Br}^{\mathrm{SM}}(ZZ)$
150	100%	100%
200	100%	100%
300	71%	71%
350	75%	76%
400	80%	81%
450	83%	84%

$m'_E = m''_E = 100$ GeV
$m'_N = m''_N = 100$ GeV

m_h (GeV)	$\mathrm{Br}/\mathrm{Br}^{\mathrm{SM}}(WW)$	$\mathrm{Br}/\mathrm{Br}^{\mathrm{SM}}(ZZ)$
150	27%	28%
200	74%	75%
300	73%	74%
350	78%	79%
400	83%	84%
450	86%	87%

$m'_E = m''_E = 100$ GeV
$m'_N = m''_N = 70$ GeV



$$m'_E = m''_E = m'_N = m''_N \equiv m_L$$

CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

$|V_{ud}| = 0.97425 \pm 0.00022$ $|V_{us}| = 0.2252 \pm 0.0009$ $|V_{ub}| = (3.89 \pm 0.44) \times 10^{-3}$

$|V_{cd}| = 0.230 \pm 0.011$ $|V_{cs}| = 1.023 \pm 0.036$ $|V_{cb}| = (40.6 \pm 1.3) \times 10^{-3}$

$|V_{td}| = (8.6 \pm 0.6) \times 10^{-3}$ $|V_{ts}| = (38.7 \pm 2.1) \times 10^{-3}$ $|V_{tb}| = 0.88 \pm 0.07$

[PDG '10]

Mixings between ordinary generation and 4th generation are constrained by unitarity of CKM matrix and meson decays

e.g., $|V_{ub'}| < 0.06, |V_{cb'}| < 0.027, |V_{tb'}| < 0.31$ @ 3σ

[Alok,Dighe,London '11]

So, one usually assumes that 4th generation decays to 3rd generation

- 4th generation top: $t' \to bW$

- 4th generation bottom: $b' \to tW \quad (m_{b'} > m_t + m_W)$

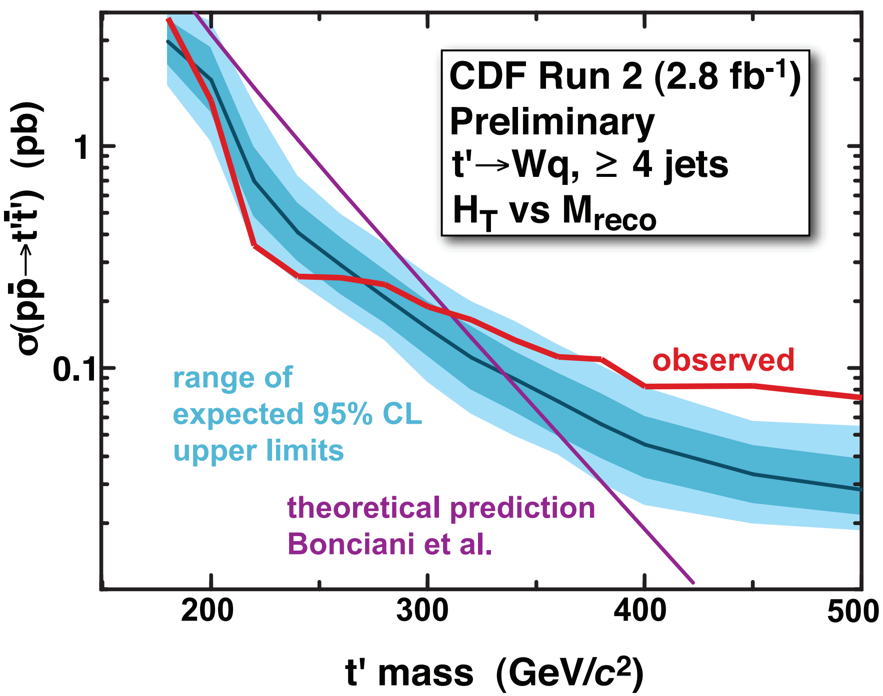
  Otherwise, bottom' decays to Z at 1-loop process,

  $b' \to bZ$

  However, the region $m_{b'} < m_t + m_W$ where this process dominates in decay mode is already excluded by [Hung,Sher '08] based on [CDF '07]

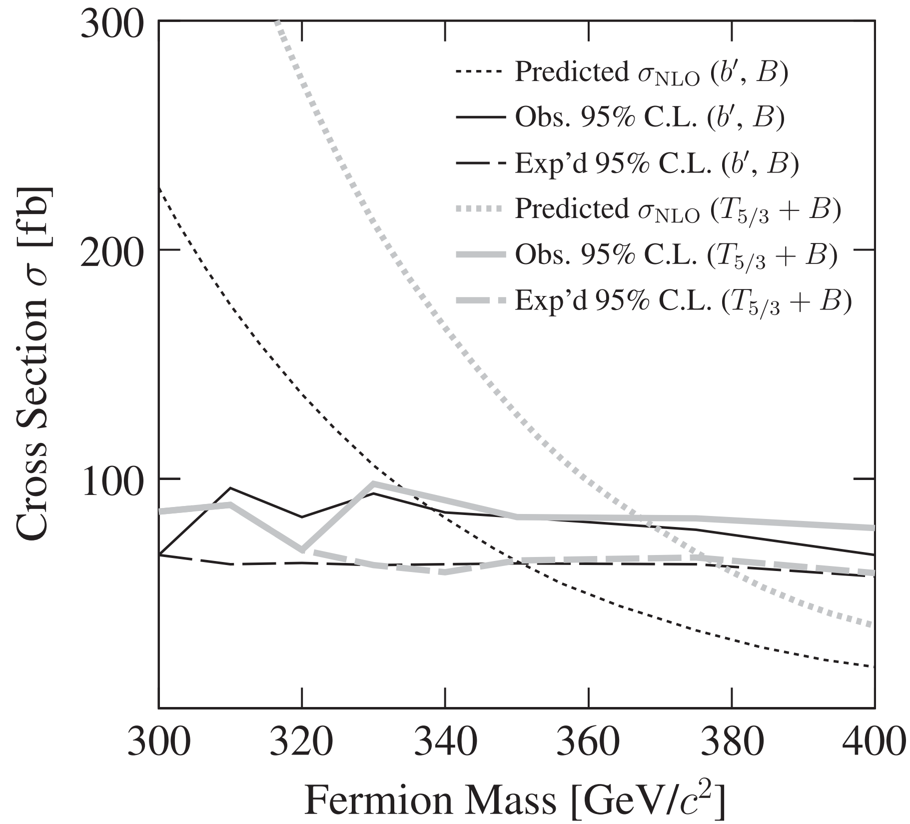
4th generation quark mass bound

Top'



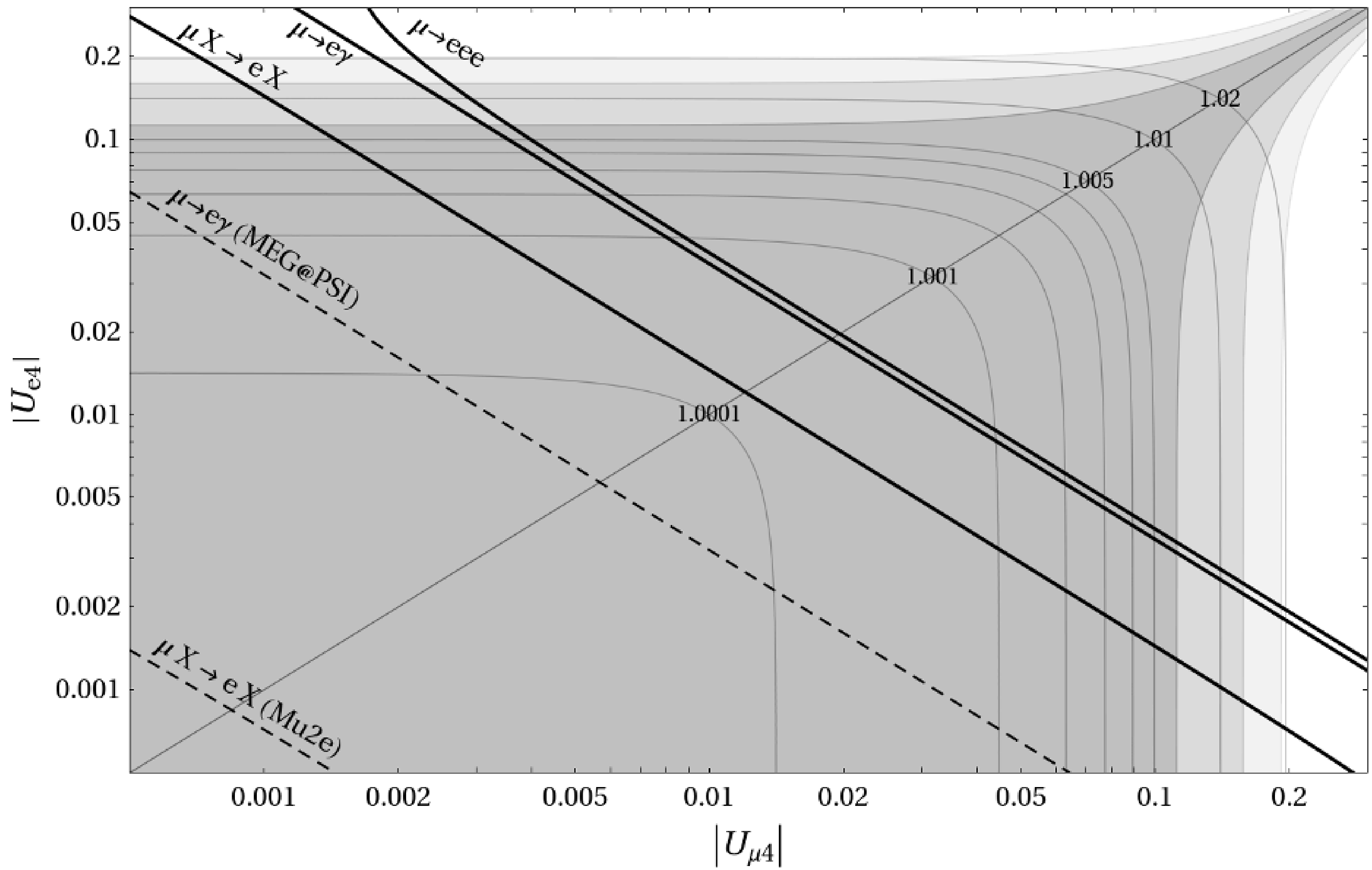
$$m_{t'} > 311 \text{ GeV}$$

Bottom'



$$m_{b'} > 338 \text{ GeV}$$

MNS matrix



[Buras,Duling,Feldmann,Heidsieck,Promberger '10]

$\rightarrow |U_{e4}U_{\mu 4}| < 10^{-4}$